SAFETY GROUNDING - A PERFORMANCE APPROACH

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ABSTRACT

Grounding, for the purpose of safety, has caused much confusion in the minds of engineers and technical personnel who are required to design or specify electrical systems. This confusion stems from the fact that the majority of electrical standards used today are design oriented and do not clearly specify the goal to be achieved. Grounding for safety becomes confusing in current literature because of the liberal interpretation of grounding. It sometime means system grounding, equipment grounding or a combination of both. A benefit of specifying safety grounding in performance language is that it allows for new and future technology to be used in developing a safe grounding system. This paper will explain the flexibility of using performance oriented language for specifying safety grounding. The logic behind the performance language for safety grounding will be explained along with the parameters and assumptions used to develop the performance specification. In addition, practical application of the performance approach will be explained along with some specific examples.

INTRODUCTION

Grounding of electric circuits and electrical equipment frames are two subjects which on the surface seem simple. However, the application of the techniques becomes complex and at times confusing. Grounding in electrical terms also carries a dual meaning. It can refer to how an electric circuit or system is connected to earth or it can refer to how an enclosure of an electric circuit or system is connected to earth. It is because of this dual meaning of grounding that an approach to grounding should be taken that states the goal. One connotation that grounding carries with it is that grounding is performed to provide safety to personnel. Providing safety to personnel is usually interpreted to mean that any electrical equipment frame a person touches or comes in contact with will not be an electric shock hazard. By properly grounding frames, voltages that may be hazardous to personnel are eliminated. When large power systems are operated at high voltages, merely interconnecting all the frames of the electric equipment to ground may not be enough to protect personnel from hazardous voltages. It may require that the grounding circuit of the power system be designed and constructed in a manner to limit exposure voltages to safe levels and durations.

Many accidents can be cited where electrical equipment frames were connected to earth but the frames presented a shock hazard. This is dramatically illustrated in the following fatal accident that occurred at a sand and gravel operation. Two hours prior to the accident an electrical contracting firm had finished grounding the crusher. As seen from figure 1, the grounding consisted of a driven ground rod and a conductor connecting it to the crusher. When the 3 phase electric motor developed a grounded phase in its junction box, the frame of the hopper became energized. When the employee touched the hopper frame he was electrocuted.

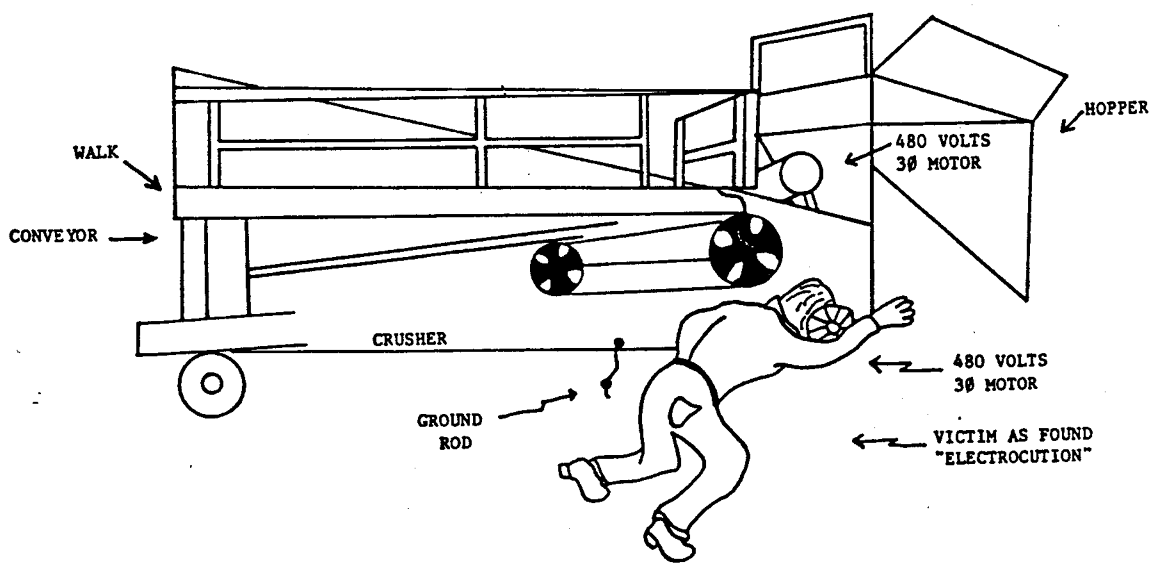

Figure 1. Peg Grounding

These accidents occur because the electrical principles of safety grounding are not followed. Today electrical codes and handbooks go into great detail as to how a grounding conductor should be mechanically and physically installed. However, the goal of why the grounding conductor is needed is usually not stated at all or understated. It is for these reasons that a performance approach to grounding should be taken.

GROUNDING OBJECTIVE

The objective of grounding equipment frames is to protect personnel from hazardous voltages. Equipment grounding, as treated by many codes, deals with the interconnection of equipment frames and the earth with conductors. They do not indicate that consideration should also be given to the power system protective devices and how the power system is connected to earth. Since a performance approach to grounding should take into account both equipment and system grounding the term “safety grounding” will be used in this paper to describe this type of grounding. The objective of safety grounding is to protect personnel from hazardous voltage levels and durations that may appear on equipment frames due to abnormal conditions.

Work conducted by Charles Dalziel and adopted into IEEE Standard 80-1976 is the foundation for safety grounding. The equation $I^2t = 0.0135$ developed by Dalziel describes a current-time relationship, based on empirical data. This equation is valid for shock durations within the range of .03 to 3 seconds. Currents and times which yield values below this constant will not cause ventricular fibrillation to 99.5% of the people who encounter them.

It is obvious, therefore, that a performance approach to grounding would include the use of Dalziel's equation $I^2t = 0.0135$. However, as stated earlier the objective of safety grounding is to prevent hazardous voltages from appearing on frames of equipment. It would, therefore, be beneficial to relate voltage and the duration of the voltage to a constant. To do this a value for resistance will have to be determined.

RESISTANCE

The resistance value to be used must consider the person's contact resistance, the body resistance and the earth resistance of the return path. Figure 2 illustrates the body, contact, and earth resistance in relationship to the power system feeding the electrical machine.

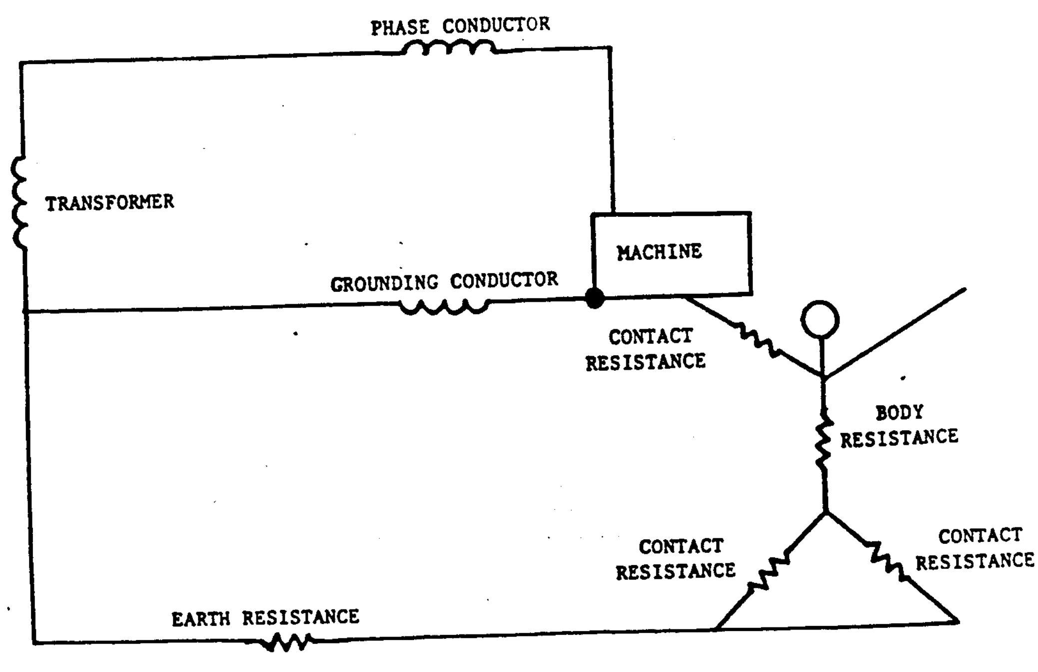

Figure 2. Resistance

Published values for body resistance range from 500 ohms to 3000 ohms. IEEE 80-1976 uses a figure of 1000 ohms to represent the resistance of the body from hand to both feet and the resistance from one foot to the other. Underwriters Laboratory's (UL) "943 standard for ground-fault circuit interrupters" uses a 1500 ohm resistance in determining the leakage current a body would be subjected to when touching the frame of electric equipment. The UL value simulates total resistance including body resistance. The value of 1500 ohms would therefore include the 1000 ohms that IEEE 80-1976 assumes for body resistance and leave 500 ohms to take into account earth resistance and contact resistance. This paper will use the 1500 ohm value in developing the performance criteria for safety grounding. It will be shown later that the 1500 ohm value is reasonable and provides protection against a hazardous shock.

VOLTAGE

It is obvious, that since a value of resistance has been established, Dalziel's equation $I^2t = 0.0135$ can be expressed in terms of voltage. Letting $I=(V/1500)$ and substituting into the equation $I^2t = 0.0135$, the voltage time relationship can be obtained. The equation becomes $V^2t=30375$. Voltages and times which yield values below this constant will not cause ventricular fibrillation to 99.5% of the people who are exposed to them. Inherent in the $V^2t=30375$ equation is the assumption that the body and contact resistance is 1500 ohms. Just as Dalziel's equation relates current and time, this equation which relates voltage and time is valid for the time range of .03 seconds to 3 seconds. By substituting these two values, the $V^2t=30375$ equation yields a voltage range of 1000 to 100 volts respectively. This is graphically illustrated in Figure 3.

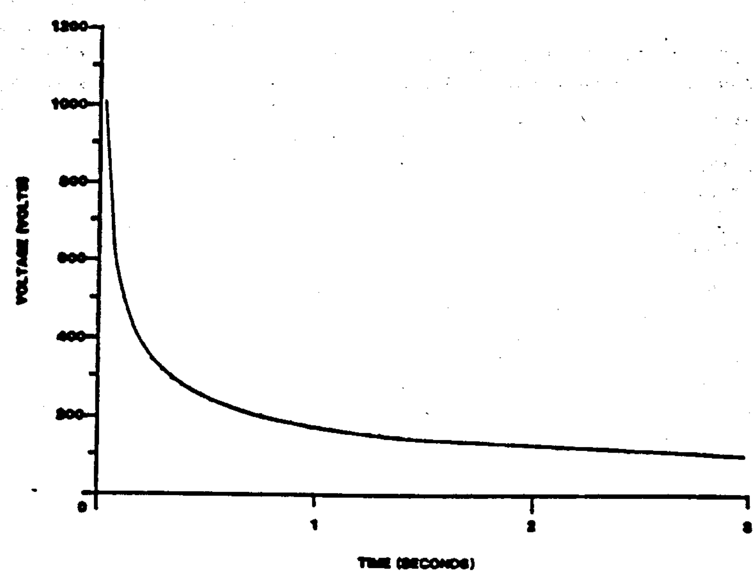

Figure 3. Voltage Exposure Curve (3 Seconds)

Even though, the lowest voltage for which the equation is valid, is 100 volts, it should not be inferred that all voltages below 100 volts are safe. Mine Safety and Health Administration's accident data documents accidents where miners have been electrocuted at voltages less than 100 volts.

A typical example is a welder who was killed from contacting the energized electrode of an electric welder with his neck. The voltage was approximately 80 volts. However, the conditions were such that a voltage of this low a value was fatal. MSHA has no documented fatalities at voltages less than 48 volts. This voltage level has also been accepted as a safe level on bare signal wires accessible to contact by persons as stated in the Metal and Nonmetal Standards 55/56/57.12012. It is obvious that voltages below 100 volts should be cleared within a reasonable time. Voltages between 48 and 100 should have a definite time stated that they can exist on frames of equipment. It is proposed that the range of times for voltages between 48 and 100 volts be determined by the $V^2t=30375$ equation. This then extends the $V^2t=30375$ curve from .03 to 3 seconds to .03 to 13 seconds. This is graphically illustrated in figure 4.

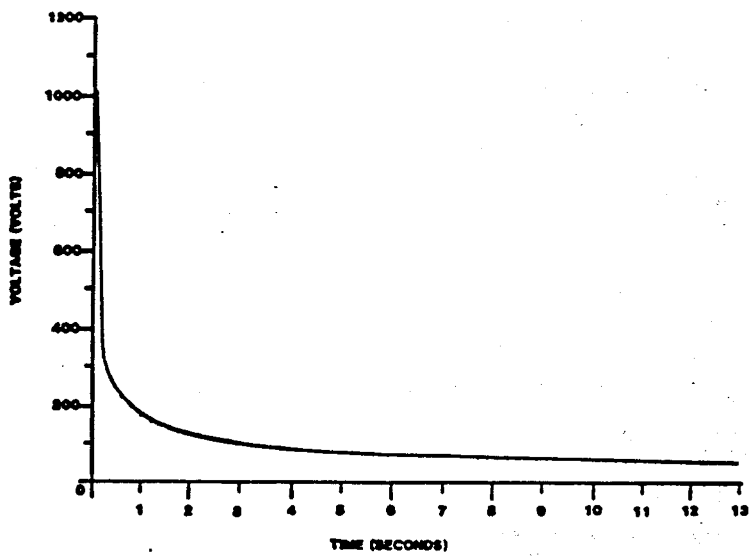

Figure 4. Voltage Exposure Curve (13 Second)

CLEARING TIMES

Clearing times of less than .03 seconds (approximately 2 cycles) cannot be considered reliable for the protection of persons from shock. By substituting .03 seconds into the $V^2t=30375$ equation the voltage permitted would be 1000 volts. Therefore, frames of electric equipment should never expose persons to voltages above 1000 volts. By substituting 100 volts into the equation this voltage would have to be cleared within 3 seconds. This is a reasonable time and can easily be achieved with conventional circuit protective devices. In the voltage range between 48 and 100 volts the clearing time range would be 13 seconds to 3 seconds. This range is also easily achieved with conventional circuit protective devices.

The proposed performance approach would classify exposure voltages up to 48 volts as undesirable from a shock hazard perspective and good engineering practices would not permit these voltages to exist indefinitely.

PERFORMANCE GROUNDING

It becomes clear that a performance approach would remove voltages of less than 48 volts within 13 seconds and remove voltages above 48 volts within the times determined by the equation $V^2t=30375$. Since the approach assumes a resistance of 1500 ohms, a logical question would be “is this value reasonable?” The 1500 ohms can be assumed to be a reasonable value if the equation $V^2t=30375$ yields a soil resistivity which is considered practical when applied to a touch potential situation. Since most electric shocks occur when a person touches something, the touch potential equation derived in IEEE Standard 80-1976 section 4 will be used. This equation is:

$$E = \frac{116+0.17P}{\sqrt{t}}$$

where:

t = time in seconds.
P=earth resistivity in ohm meters.
E=touch voltage in volts.

Squaring both sides of the equation and rearranging terms yields:

$$E^2t = 13456+39.44(P)+0.029(P)^2$$

IEEE Standard 80, Section 8.1 lists various oil resistivities in Table 1. Using these values and the equation above, we have the following results:

TYPE GROUND	OHM-METERS RESISTIVITY (p)	E^2t
Wet Organic Soil	10	13856
Moist Soil	10^2	17690
	3.42×10^2	30375
Dry Soil	10^3	81896
Bed Rock	10^4	3307856

As can be seen from the above table, the equation ($V^2t = 30375$) applies when the soil resistivity is approximately 3.42×10^2 ohm-meters. This value falls between moist soil and dry soil. It is not uncommon for a person to find himself standing in wet soil which is 1/30 times the resistivity of 3.42×10^2 ohm-meters. Therefore, it is concluded that this is a reasonable approach.

The 1500 ohm value includes 1000 ohms for body resistance and an earth resistance based upon a soil resistivity of 3.42×10^2 ohm-meters. It does not allow for contact resistance assuming it to be zero. Due to the variations of body resistance and soil resistivity, this assumption is reasonable.

APPLICATION

So far the performance approach has specified the upper limit of voltages and their times which can energize equipment frames without causing a hazard. Since this approach would be used on all types of power systems, guidelines as to how to apply it must be determined. The resistance value of 1500 ohms factors in the body resistance and earth resistivity assuming zero contact resistance. Therefore, once the voltage rise on a machine is determined this voltage would be the value used to calculate the exposure time using the equation $V^2t = 30375$.

To determine the voltage on a machine frame, the maximum available current under a ground fault condition must first be determined. For solidly grounded power systems this would be the maximum phase to ground fault current. When a system is impedance grounded, the fault current would be limited by the impedance of the grounding device. On these systems, the reduced current would be the value used as the maximum ground fault current. When ungrounded systems experience a ground fault minimal fault current flows. Because of this a single ground fault is usually not detected, and it is only after the second fault that the ungrounded delta experiences problems. For these systems the method to determine maximum ground fault current would be to assume a ground at the power source and another ground on an opposite phase at the equipment frame. This in effect places the grounding conductor phase to phase and allows for easy calculation of the ground fault current. It is obvious that the greatest ground fault current occurs on ungrounded systems with two faults and the least ground fault current occurs on impedance grounded systems.

Once the ground fault current is determined, it is a simple matter of calculating the voltage elevation that will occur at the machine frame by using the ground wire impedance. This would be the voltage that a person may experience when touching the machine frame. By using this voltage and the equation $V^2t = 30375$ a time can be calculated. This time would be the maximum time that the voltage can exist on the machine frame. Circuit protection devices can then be sized and coordinated to eliminate the voltage within this exposure time.

Two assumptions are made when applying the equation $V^2t = 30375$; one is that the earth return path has zero resistance when calculating the voltage time exposure, the other is that the earth return path is infinite when calculating the voltage rise on equipment frames. These two assumptions may appear contradictory. However, the first assumption that the earth return path is zero is actually taken care of in using the 1500 ohm value when deriving he equation $V^2t = 30375$, the other assumption that the return path is infinite when calculating the equipment voltage rise, is valid since earth cannot be relied upon as a grounding conductor. IEEE 80-1976, section 8.1, Table 1 shows that earth resistivity can vary considerably. Also, the IEEE "Green Book" Standard 142-1982 states that, "earth is inherently a rather poor conductor." Sound engineering practices do not advocate the use of earth as a reliable conductor to be used as a safety grounding conductor. It is therefore reasonable to assume infinite resistance for the earth ground return. This then requires all the fault current to flow through the safety grounding conductor back to the system's connection to earth.

EXAMPLE

The following examples will demonstrate the application of safety grounding of a typical installation at a phosphate mine. The system shown in figure 5 will be used for the demonstration.

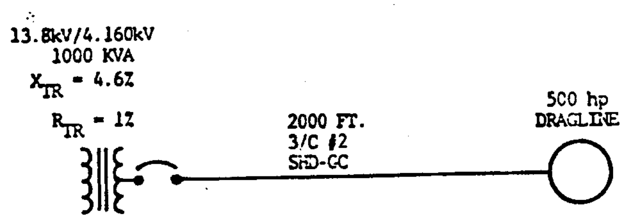

Figure 5. Open Pit Mine Circuit

For worst case analysis the primary of the transformer will be assumed to have an infinite current source. In addition, the analysis uses estimates of the ground wire impedances. A circuit analysis of the secondary circuit will be conducted using the impedances of the cables and transformer.

Transformer Z:

$$R_{tr} = \frac{10(\%R)(kV_{22})^2}{kVA}$$

$$R_{tr} = \frac{10(1)(4.16)^2}{1000}$$

$$R_{tr} = 0.173 ohms$$

$$X_{tr} = \frac{10(\%X)(kV_{22})^2}{kVA}$$

$$X_{tr} = \frac{10(4.6)(4.16)^2}{1000}$$

$$X_{tr} = 0.796 ohms$$

No. 2 AWG Cable:
Phase Conductor (from Tables)

R_c = 0.201 ohms/1000 feet

X_c = 0.036 ohms/1000 feet

Ground Wire No. 6 AWG (Estimated from Tables)

R_{G1} = 0.51 ohms/1000 feet

X_{G1} = 0.041 ohms/1000 feet

Solid Grounded Wye Secondary

Figure 6 depicts a solidly grounded WYE system with a ground fault at the load.

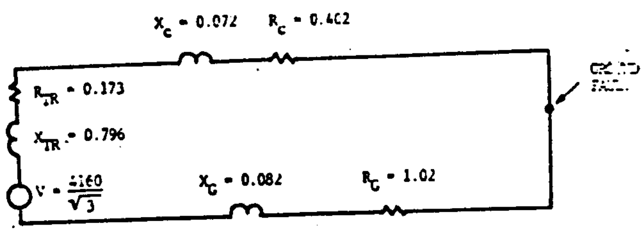

Figure 6. Solidly Ground WYE

The total circuit impedance becomes:

$$Z_T = 1.595 + j\,0.95$$

$$Z_T = 1.856 \angle 30.7°$$

Finding the phase-to-ground current:

$$I_{2G} = \frac{V}{Z_T} = \frac{4160}{\sqrt{3}\,(1.856 \angle 30.7°)}$$

$$I_{2G} = 1294 \angle -30.7°$$

Once the phase-to-ground current is obtained the voltage drop in the safety grounding conductor can be calculated as:

$$V = Z_G \times I_{2G}$$

$$V = 1.023 \angle 4.59^\circ \times 1294 \angle -30.7^\circ$$

$$V = 1324 \angle -26.16^\circ$$

With 1324 volts dropped in the grounding circuit under fault conditions the equation $V^2t = 30375$ will determine the clearing time which must be achieved to eliminate a shock hazard.

Using this equation we obtain:

$$V^2 t = 30375$$

$$t = \frac{30375}{(1324)^2}$$

$$t = 0.017 \textit{ seconds}$$

$$t = 1.04 \textit{ cycles}$$

Ungrounded Delta Secondary

The ungrounded delta must be analyzed the same as a corner grounded delta since this is the worst case. For this case a fault is assumed at the source transformer and a second fault is assumed at the load in question. Figure 7 depicts the ungrounded delta configuration with a ground fault at the load.

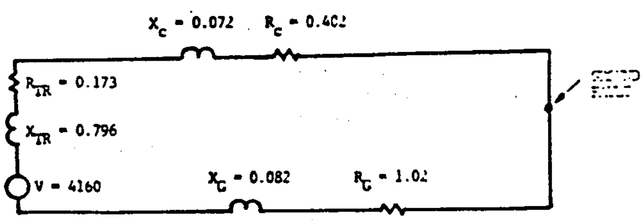

Figure 7. Ungrounded Delta System

The total circuit impedance becomes:

$$Z_T = 1.595 + j0.95$$

$$Z_T = 1.856 \angle 30.7^\circ$$

Finding the fault current:

$$I_{2G} = \frac{V}{Z_T} = \frac{4160}{1.856\ \angle 30.7°}$$

$$I_{2G} = 2241\ \angle -30.7°$$

The voltage in the safety grounding conductor is calculated to be:

$$V_G = I_{2G} \times Z_G$$

$$V_G = 2241\ \angle -30.7° \times 1.023\ \angle 4.596°$$

$$V_G = 2293\ \angle -26.2°$$

In this case 2293 volts is present on the safety grounding conductor. Solving $V^2t = 30375$ for the maximum safe exposure time yields:

$$V^2 t = 30375$$

$$t = \frac{30375}{(2293)^2}$$

$$t = 0.0058\ \textit{seconds}$$

$$t = 0.35\ \textit{cycles}$$

Resistance Grounded Wye

Figure 8 depicts the resistance grounded configuration with a ground fault at the load.

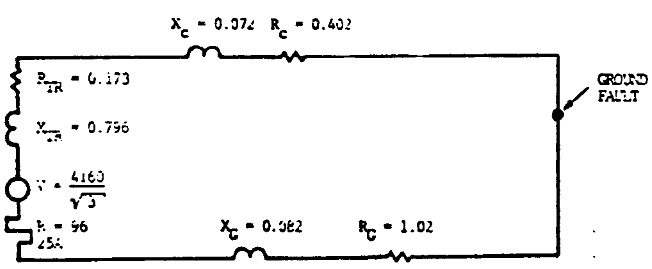

Figure 8. Resistance Grounded System

The total circuit impedance is:

$$Z_T = 97.595 + j\,0.95$$

$$Z_T = 97.6 \angle 0.558^\circ \ ohms$$

The fault current becomes:

$$I_{2G} = \frac{V}{Z_T} = \frac{4160}{97.6 \angle 0.558^\circ}$$

$$I_{2G} = 24.6 \angle -0.558^\circ \ Amperes$$

The voltage in the safety grounding conductor is calculated to be:

$$V_G = I_{2G} \times Z_G$$

$$V_G = 24.6 \angle -0.558^\circ \times 1.023 \angle 4.596^\circ$$

$$V_G = 25.17 \angle 4.038^\circ \ volts$$

In the case of this resistance grounded system, 25 volts is present on the safety grounding conductor. Solving $V^2t = 30375$ for the maximum safe exposure time yields:

$$V^2 t = 30375$$

$$t = \frac{30375}{(25)^2}$$

$$t = 48.6 \ seconds$$

$$t = 2916 \ cycles$$

Table 1 summarizes the data for the three system configurations.

SYSTEM	EXPOSURE TIME
Ungrounded Delta	0.35 cycles
Solidly Grounded WYE	1.04 cycles
Resistance Grounded WYE	2916 cycles or 48.6 seconds

Table 1. Maximum Safe Exposure Times

This system is used to mine phosphate. It is operating in the resistance grounded configuration with any ground faults set to be cleared instantaneously or within about 8 cycles.

It can be seen that a very large margin of safety exists with a resistance grounded system over the other two configurations. In fact with the use of relayed oil circuit breakers the voltages could not be cleared from the equipment within the maximum safe exposure times for the solidly-grounded wye and the ungrounded delta systems.

It should be noted that grounding resistors are usually rated at 10 seconds which will allow sufficient time to coordinate ground faults.

The minimum time for a protective device to clear a fault is dependent upon many physical constraints and cannot be expected to be faster than 5 cycles for an oil circuit breaker or about 2 cycles for a molded case circuit breaker.

If the calculations determine that the safe exposure time is less than eight cycles with a high voltage system then the system needs to be resistance grounded to limit the voltages to within the safe exposure values.

On low voltage circuits the safe exposure times are considerably longer than molded case circuit breaker clearing times and thereby allow some latitude in achieving shock prevention.

CONCLUSIONS

By stating how the safety grounding system should perform, the reason why we ground electric equipment and circuits becomes clear. When grounding conductors are installed they are not being installed just to comply with a regulation in some code. They are being installed to prevent hazardous voltage from appearing on equipment frames. Also when systems are grounded or ungrounded it becomes clear why the timing of protective devices used on the systems is an important factor in limiting the duration that voltages exist on machine frames. They can be used to limit voltage exposure time to a safe value. This then consolidates the power system design philosophies and the equipment grounding system philosophies into a safety grounding system. This safety grounding system then provides protection to personnel from hazardous voltage exposure determined by the equation $V^2t = 30375$.

The performance approach to grounding would by no means eliminate the need for existing electrical codes on equipment and system grounding. It does however augment these codes by stating the objective of grounding. In addition, by stating how the safety grounding should perform, future methods and devices can be evaluated for proper protection.